Renewable and Sustainable Energy Reviews 13 (2009) 1230–1245

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

The economical and environmental performance of miscanthus and switchgrass production and supply chains in a European setting

Edward M.W. Smeets *, Iris M. Lewandowski, André P.C. Faaij

Copernicus Institute for Sustainable Development and Innovation, Department of Science, Technology and Society, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands

ARTICLE INFO

Article history:
Received 15 August 2008
Accepted 9 September 2008

Keywords:
Miscanthus
Switchgrass
Costs
Soil erosion
Biodiversity
Water
Greenhouse gas emissions
Primary energy use

ABSTRACT

The purpose of this study is to analyse the economical and environmental performance of switchgrass and miscanthus production and supply chains in the European Union (EU25), for the years 2004 and 2030. The environmental performance refers to the greenhouse gas (GHG) emissions, the primary fossil energy use and to the impact on fresh water reserves, soil erosion and biodiversity. Analyses are carried out for regions in five countries. The lowest costs of producing (including storing and transporting across 100 km) in the year 2004 are calculated for Poland, Hungary and Lithuania at 43–64 € per oven dry tonne (odt) or 2.4–3.6 € GJ^{-1} higher heating value. This cost level is roughly equivalent to the price of natural gas (3.1 € GJ^{-1}) and lower than the price of crude oil (4.6 € GJ^{-1}) in 2004, but higher than the price of coal (1.7 € GJ^{-1}) in 2004. The costs of biomass in Italy and the United Kingdom are somewhat higher (65–105 € odt^{-1} or 3.6–5.8 € GJ^{-1}). The doubling of the price of crude oil and natural gas that is projected for the period 2004–2030, combined with nearly stable biomass production costs, makes the production of perennial grasses competitive with natural gas and fossil oil. The results also show that the substitution of fossil fuels by biomass from perennial grasses is a robust strategy to reduce fossil energy use and curb GHG emissions, provided that perennial grasses are grown on agricultural land (cropland or pastures). However, in such case deep percolation and runoff of water are reduced, which can lead to overexploitation of fresh water reservoirs. This can be avoided by selecting suitable locations (away from direct accessible fresh water reservoirs) and by limiting the size of the plantations. The impacts on biodiversity are generally favourable compared to conventional crops, but the location of the plantation compared to other vegetation types and the size and harvesting regime of the plantation are important variables.

Contents

* Corresponding author. Tel.: +31 30 253 7688; fax: +31 30 253 7601.
E-mail address: E.M.W.Smeets@uu.nl (Edward M.W. Smeets).

1364-0321/$ – see front matter
doi:10.1016/j.rser.2008.09.006

1. Introduction

The present use of fossil fuels in the European Union (EU) has several disadvantages. First, the use of fossil fuels is a major contributor to environmental pollution through the emission of air pollutants and greenhouse gases (GHGs). Second, roughly half of the primary energy consumed in the EU is supplied by imports and this percentage is expected to increase to 70% by 2030, assuming no significant changes in policies take place [1]. The political instability of some of the key exporting regions potentially threatens stable production and thereby jeopardises the energy security of the EU. Biomass can be used as a substitute for fossil fuels and may reduce the dependence on imports and/or the carbon dioxide emissions. Consequently, the EU and also several EU member states have developed policies to promote the use of biomass energy sources. For example, the EU aims at increasing the use of liquid biofuels for transportation from the present 2% in 2005 to 10% in 2020 and increasing the share of renewable energy of the total primary energy consumption from 6.4% in 2004 to 20% in 2020 and whereby bioenergy is expected to play an important role [2]. These targets are combined with sustainability demands (e.g. with respect to GHG emissions and other environmental impacts) [3].

Miscanthus and switchgrass are two species of perennial grasses that can be used for various energy and material applications [4]. Advantages of grasses over annual energy crops such as cereals, sugar beet and rapeseed are the relatively high net fossil energy and GHGs emission saving per unit of biomass and per unit of agricultural land [5]. Biomass from grasses is currently mainly used for co-combustion with coal and direct combustion for heat and power applications, but can be used for a wide range of energy and material applications, such as for the production of heat and power via combustion and/or gasification, for the production of liquid biofuels, but also for the production of paper, construction material and plastics. The options for future uses of miscanthus and switchgrass depend to a considerable degree on the economical and environmental performance of the production, storage and transportation of biomass.

Various studies have been carried out that focussed on the economical performance (e.g. [6,7–12]) and on the environmental performance [10,13–20] of the production and application of miscanthus and switchgrass biomass. Most studies considered one specific site, region or country, or a specific soil profile, production and transportation system. Little attention was paid to short- and long-term improvement options and to the sensitivity of the results for changes in the input data.

Therefore, the aim or our research is to provide insight into the possibilities and limitations to minimise the costs and optimise the production towards maximum production capacity and minimum environmental impacts of miscanthus and switchgrass production in the EU. Specific attention is thereby paid to differences in natural circumstances (soil, climate) and also in the costs of inputs (land, labour, agro-chemicals), which is particularly relevant when comparing West Europe (the EU15) and East Europe (the 10 new EU member states). Results are generated for the years 2004 and 2030 for five regions in five countries that (partially) represent the variability of the mentioned factors found in the EU25.

2. Methodology

2.1. Selection of case study regions

Five regions in five countries are selected that are potentially promising producers as described in Table 1. The countries are chosen so that they represent (some) of the variability in yields, but particularly the differences in costs of land and labour between West Europe (the EU15) and East Europe (the 10 new EU member states).

2.2. Yields

Crop yields are a crucial parameter for both the environmental and economic performance. Miscanthus yields under rain fed and non-nutrient limiting conditions in the year 2004 are calculated using a spreadsheet model specifically developed for the prediction of miscanthus yields [21]. The model predicts the yields in autumn, but postponing of the harvest until spring is common practice, because it improves the quality of the harvested biomass (the nutrient and moisture content of the harvested biomass are reduced) and despite a yield loss of one-third due to decay [22]. Because no model similar to estimate switchgrass yields is available in this study switchgrass yields are assumed to be 80%

Table 1
Rationale for selection of the five regions for which results are generated.

Region	Rationale and description
Lubelski – North West Poland	Poland is a promising bioenergy producing region, because of three reasons. (1) The high availability of land for energy crop production. Poland is the country with the second to highest availability of surplus arable land that is potentially available for energy crop production. In the year 2010 and 2030, 27% and 31% of the total agricultural area are available for energy crop production, respectively [30,81]. These values take into account the demand for land for the production of food as well as ecological limitations. (2) The high yield of miscanthus and switchgrass estimated for Poland, namely 15 and 12 odt ha^{-1} y^{-1}, respectively [21]. (3) The low costs of energy crop production due to the relatively low price of land, labour and other inputs [30]. Lubelski is chosen, because it is one of the most important centres of agricultural production in Poland and because Lubelski is projected to have one of the highest miscanthus and switchgrass yields in the country, 19 and 15 odt ha^{-1} y^{-1}, respectively [21]. Moreover, Lubelski is classified as one of the regions in the EU25 with the highest percentage of the area of agricultural land: more than 31% of the total land surface in Lubelski is potentially available for energy crop production in the year 2030 [33].
Del-Dunantal – South West Hungary	Hungary is selected for the same reasons as Poland. Del-Dunantal is chosen, because this region is classified as a region with a very high percentage of the area of agricultural land: in the year 2030 more than 31% of the total land surface is potentially available for the production of energy crops energy crop production in the year 2030 [33]. Further, Del-Dunantal is projected to have the highest miscanthus and switchgrass yield in the country and one of the highest yields in the EU25, namely 20 and 16 odt ha^{-1} y^{-1}, respectively [21].
Devon – South West United Kingdom	This region is selected to show the contrast between regions in the EU15 and regions in the 10 new member states. The availability of surplus arable land is lower and the costs of land, labour and other inputs are higher in EU15 regions compared to regions in the new member states. Devon is classified as one of the regions in the EU15 with the highest availability of surplus arable land that is potentially available for energy crop production in the year 2030: 17–31% of the total area of land is available in the year 2030 [33]; higher values are only found in the new member states. Devon is estimated to have a relatively high yield compared to other regions in the United Kingdom and is also "BICAL" area. BICAL is a farmer's co-operative that commercially grows several thousands of hectares of miscanthus in the UK and is the largest miscanthus producer in the EU25.
Lombardia – North Italy	Italy is selected for the same reasons why the United Kingdom is selected. Further, Lombardia is an important centre of agriculture in Italy and also in the EU25, thanks to its fertile soils on the padana plains and favourable temperate climate with a year-round rainfall pattern, but with a longer growing period compared to more northern regions. The availability of surplus arable land for energy crop production is limited (6.5–12% of the total area of land in Lombardia [33]), but the high yields (the highest in the EU25 [21]) make this region a promising bioenergy producer with costs that are projected to be above those realized in East Europe, but below those in other EU15 countries [33].
Lithuania	The rationale for selecting Lithuania is the same as for Poland and Hungary. Lithuania has the highest availability of surplus arable land that is potentially available for energy crop production of all countries in the EU25 in the year 2030: 42% of the total agricultural area is available for energy crop production, respectively [30,81]. The yields are somewhat lower compared to some other EU25 countries [21], but the costs of land and labour are among the lowest in the EU25, which make this country a promising bioenergy producer [30]. Lithuania is not divided into regions, because of the relatively small size of the country.

of the miscanthus yields [23]. Breeding and general (bio)technological improvements are expected to increase crop yields Elbersen et al. [24] estimated that switchgrass yields will increase (exponentially) 2% y^{-1}. Clifton-Brown [23] assumed a (non-exponential) yield increase of 0.8% y^{-1}. We assume a (non-exponential) yield increase of 1.5% y^{-1}, with a bandwidth of 1.0% y^{-1} and 2.0% y^{-1}. Table 2 shows the yields in the five regions included in our analysis in the year 2004 and 2030, expressed in oven dry tonne (odt). The higher heating value of miscanthus and switchgrass assumed in this study is 18.3 GJ odt^{-1} [25].

2.3. Economics of miscanthus and switchgrass production

The costs of miscanthus and switchgrass supply chains are calculated following the equation below (adjusted from [26]).

$$C = \frac{\sum_{i=1}^{i_t} (\mathrm{ecc}_i \sum_{y=1}^{n} f_i(y)/(1+\mathrm{dr})^y)}{\mathrm{yld}\,\mathrm{rot} \sum_{y=1}^{n} f_{\mathrm{yld}}(y)/(1+\mathrm{dr})^y}$$

where i_t = the number of cost items with different time pattern, see Table 3 (dimensionless); C = costs of biomass (€ per oven dry tonne); yld = yield of the energy crop, based on rainfed production, see Table 2 (oven dry tonne per hectare per year); rot = rotation cycle (year); n = number of years of plantation lifetime (year); ecc_i = cost of energy crop cost item (€); $f_i(y)$ = number of times that cost item i is applied on the plantation in year y (dimensionless); dr = discount rate (dimensionless) and $f_{\mathrm{yld}}(y)$ = the binary number, harvest (1) or not (0) in year y (dimensionless).

Table 2
The yield of miscanthus and switchgrass in the five regions included in our analysis in the year 2004 and 2030 (in odt ha^{-1} y^{-1}; spring harvesting). *Sources*: [21–23].

	Miscanthus		Switchgrass	
	2004	2030	2004	2030
Poland – Lubelski	19	27	15	21
Hungary – Del-Dunantal	20	27	16	22
United Kingdom – Devon	15	21	12	17
Italy – Lombardia	25	34	20	27
Lithuania	17	23	13	18

The management scheme and rotation cycle depicted in Table 3 is applicable for both miscanthus and switchgrass. No distinction in management could be made between different soil types, climate profiles or countries due to a lack of data on management options.

For each cost item in Table 3 an estimate is made for the share of labour, materials (e.g. planting materials and chemicals) and machinery (includes depreciation, maintenance and fuel) within the total costs. All costs and benefits are spread out equally over the years and expressed in net present value (NPV) in euro's in 2004. Next, the costs of storing, transporting and pelletizing (optional) are added. Regional variation in economic performance is included by means of differences in natural circumstances (yield) and fertilizer application rate (which depends on the yield). Also the prices of land, fuel, labour and fertilizer vary between regions.

Calculations are carried for the year 2004 using data from the literature. Projections for 2030 are calculated taking into account technological progress (e.g. increase of the work capacity of machinery and increase of the yield), but also changes in the price of inputs (e.g. labour, diesel).

2.3.1. Agricultural machinery

The costs of agricultural machinery (in € h^{-1}) are calculated following standardised methodologies to estimate the costs of

Table 3
The management of miscanthus and switchgrass over a production cycle of 15 years and the cost items. *Sources*: [66,42,4,7,8,34–36,38,43].

Cost category	Cost item	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Land rent	Land rent	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Establishment – soil preparation	Ploughing	1														
	Power harrowing	2														
Establishment – planting/seeding	Planting	1[a]														
	Rolling	1/2[b]														
Fertilizing	Fertilizing		2	1	2	1	2	1	2	1	2	1	2	1	2	1
	Liming				1				1				1			
Weeding	Spraying	1														
	Weed cultivating	1	1													
Mowing (only switchgrass)	Mowing	1														
Harvesting	Harvest		1	1	1	1	1	1	1	1	1	1	1	1	1	1
Removing	Rotary cultivating															2
	Spraying															1

[a] Miscanthus is planted using a rhizomes planter; switchgrass is sown using a seed drill.
[b] Miscanthus and switchgrass require one and two times rolling, respectively.

Table 4
An example of the methodology and input data used to calculate the costs of machinery. Data are for a self-propelled harvester chopper operated by a contractor for Germany in the year 2004. *Sources*: see Table 7.

Fixed costs	Value	Unit	Variable costs	Value	Unit
Purchase price (PP)	185	k€	Power	80	kW
Resale value (10% of PP)	19	k€	Fuel[b]	18	$\mathrm{l\,h^{-1}}$
Depreciation	66	€ $\mathrm{h^{-1}}$	Fuel price (incl. taxes)	0.94	€ $\mathrm{l^{-1}}$
Repair and maintenance coefficient 1	0.03	–	Fuel costs	17	€ $\mathrm{h^{-1}}$
Repair and maintenance coefficient 2	2.00	–	Lubrication[c]	0.07	$\mathrm{l\,h^{-1}}$
Repair and maintenance[a]	14	€ $\mathrm{h^{-1}}$	Lubrication price	3.4	€ $\mathrm{l^{-1}}$
Depreciation period	5	y	Lubrication costs	0.2	€ $\mathrm{h^{-1}}$
Use	500	$\mathrm{h\,y^{-1}}$	Other costs (e.g. cord)	0	€ $\mathrm{h^{-1}}$
Storage (1.75% of PP $\mathrm{y^{-1}}$)	6	€ $\mathrm{h^{-1}}$	Labour[d]	1.1	$\mathrm{h\,h^{-1}}$ [d]
Insurance (0.5% of PP $\mathrm{y^{-1}}$)	2	€ $\mathrm{h^{-1}}$	Labour price	30	€ $\mathrm{h^{-1}}$
General cost (3% of PP $\mathrm{y^{-1}}$)	11	€ $\mathrm{h^{-1}}$	Labour costs	33	€ $\mathrm{h^{-1}}$
Total fixed costs	99	€ $\mathrm{h^{-1}}$	Total variable costs	50	€ $\mathrm{h^{-1}}$

[a] Repair and maintenance costs are calculated based on the following equation [ASAE, 1997 in 27]: $R = \mathrm{RF1} \times \mathrm{PP} \times (\mathrm{lt}/1000)^{\mathrm{RF2}}$, where R is the repair and maintenance costs during the total lifetime (€), RF1 the repair and maintenance coefficient 1 ($\mathrm{h^{-1}}$), RF2 the repair and maintenance coefficient 2, PP the purchase price (€) and lt is the lifetime (h) or depreciation period (y) multiplied by the use ($\mathrm{h\,y^{-1}}$).
[b] Diesel consumption is calculated based on the following equation, which is a generally accepted methodology to calculate diesel consumption originally proposed by the American Society of Agricultural Engineers [ASAE, 1997 in 27]: $D = 0.22P$, where D is the diesel use ($\mathrm{l\,h^{-1}}$) and P is the maximum power (kW).
[c] Lubrication consumption is calculated based on the following equation [7,8]: $L = 0.021 + 0.00059P$, where L is the lubrication use ($\mathrm{l\,h^{-1}}$) and P is the maximum power (kW).
[d] Labour costs (€ $\mathrm{h^{-1}}$) are calculated by multiplying the time that a machine is used (which is based on the work capacity) by 1.1 to account for the unproductive time required for travelling, servicing, lubricating and training [82].

agricultural equipment [27,28] as shown by the example in Table 4.

The costs of machinery are divided into capital, repair and maintenance, fuel, lubrication, labour, storage, insurance and other costs. Data for other machines, including data on work capacities is presented in Table 5.

The data on machine use ($\mathrm{h\,y^{-1}}$) are representative for a 50 ha farm, of which 10–20% is used for the production of perennial grasses and the rest is used for conventional agricultural crops. The 10–20% range is broadly in line with the availability of agricultural land for energy crop production projected for the year 2030 taking into account the demand for land for other purposes as well as environmental considerations. Moreover, a fraction of 10–20% of energy forest in open farmland has been estimated to be optimal for the diversity of flora and fauna, especially when the harvest is asynchronous in different sub-areas [29]. This may also be applicable to miscanthus and switchgrass (see further Section 4.2.3).

Data on the price of diesel (in € $\mathrm{l^{-1}}$, including taxes) and labour (in € $\mathrm{h^{-1}}$, including social security expenditures) in the year 2004 are derived from the Eurostat database [30]. We assume that the price of diesel (excluding taxes) doubles between 2004 and 2030, following the doubling of the price of crude oil [31]. The price of labour in the manufacturing industry is used as a proxy for the price of labour in agriculture. We also assume that the price of labour increases by 64% and 141% in West Europe (e.g. the United Kingdom and Italy) and East Europe (e.g. Poland, Hungary and Lithuania) between 2004 and 2030, which is the growth of the gross domestic product per capita projected for that period [32]. Table 6 shows the data on diesel and labour prices assumed in our analyses.

2.3.2. Land rent

Data on the (country average) price of land classified as suitable for crop production (in € $\mathrm{ha^{-1}\,y^{-1}}$) in 2004 are taken from literature [33], see Table 6. We assume that the price of cropland increases proportionally with value of the crops produced from that land and whereby the yield is used as proxy.

2.3.3. Establishment

The establishment of miscanthus and switchgrass starts with soil preparation (ploughing and harrowing). Switchgrass is

Table 5
Data on the costs and performance of agricultural machinery used in the miscanthus and switchgrass production process. *Sources*: a [27], b [83], c [84], d [7,8], e [85], f [86], g [87], h [88], i [28].

	Power (kW)	Depreciation (y)	Use[a] (h y^{-1})	Purchase price (k€)	Repair coefficients (see Table 4)		Fuel use (l h^{-1})	Lubrication (l h^{-1})	Storage (€ h^{-1})	Insurance (€ h^{-1})	General costs (€ h^{-1})	Work capacity 2004 (h ha^{-1})	Work capacity 2030 (h ha^{-1})	Additional equipment
					RF 1	RF 2								
Tractor 60 kW	60	12	800	53	0.003	2.00	13	0.06	1.2	0.3	2.0	n/a	n/a	
Tractor 75 kW	75	12	800	72	0.003	2.00	17	0.07	1.6	0.4	2.7	n/a	n/a	
Tractor 100 kW	100	12	800	75	0.003	2.00	22	0.08	1.6	0.5	2.8	n/a	n/a	
Plough	n/a	20	70	27	0.290	1.80	n/a	n/a	6.7	1.9	11.6	1.30	1.30	88 kW tractor
Power harrower	n/a	20	70	11	0.230	1.40	n/a	n/a	2.9	0.8	4.9	0.40	0.40	75 kW tractor
Rhizomes planter	n/a	10	150	18	0.320	2.10	n/a	n/a	2.1	0.6	3.5	1.00	1.00	100 kW tractor
Drill	n/a	20	70	16	0.320	2.10	n/a	n/a	3.9	1.1	6.7	0.40	0.40	60 kW tractor
Roll	n/a	20	70	13	0.160	1.30	n/a	n/a	3.2	0.9	5.4	0.32	0.32	60 kW tractor
Fertilizer spreader	n/a	10	50	4.4	0.630	1.30	n/a	n/a	1.5	0.4	2.6	0.50	0.50	60 kW tractor
Sprayer	n/a	10	100	14	0.410	1.30	n/a	n/a	2.5	0.7	4.3	0.60	0.60	60 kW tractor
Weed cultivator	n/a	10	100	5.3	0.230	1.40	n/a	n/a	0.9	0.3	1.6	0.32	0.32	60 kW tractor
Mower	n/a	20	70	12	0.180	1.60	n/a	n/a	3.0	0.9	5.2	0.50	0.50	60 kW tractor
Mounted big baler[b]	n/a	5	400	123	0,000	5.40	1.5	9.2	10.0	103	1.08	400	0.70	Three 75 kW tractors and fork loaders; two trailers
Self-propelled chopper[b]	80	5	500	185	0.030	2.00	18	0.07	6.5	1.8	11.1	0.58	0.58	Two 75 kW tractors and trailers
Trailer	n/a	12	250	25	0.190	1.30	n/a	n/a	1.7	0.5	3.0	n/a	n/a	75 kW tractor
Fork	n/a	12	250	3.0	0.007	2.00	n/a	n/a	0.2	0.1	0.4	n/a	n/a	100 kW tractor
Rotary cultivator	n/a	12	40	10	0.270	1.40	n/a	n/a	4.5	1.3	7.8	0.80	0.80	100 kW tractor
Sources	d	d, a	d	b–f, h	a	a	a	a	d	d	d	a, d, g	See text	

[a] A mounted big baler and a self-propelled chopper are prohibitively expensive when used and owned by one farmer. We therefore assume that these machines will be contractor or collectively owned.
[b] The following equation depicts the correlation between yield and harvest costs for a yield of 2–20 odt ha^{-1} y^{-1} (the R^2 of the data fit was 0.97): HF = $4.33y^{-0.589}$, where HF = harvest factor (dimensionless). The harvest factor is used to multiply the costs of harvesting (in € odt^{-1}) to correct for differences in yield. y is the yield (odt ha^{-1} y^{-1}). The HF is 1 for a yield of 12 od ha^{-1} y^{-1}. The harvesting costs are calculated by multiplying the harvesting costs based on a yield of 12 odt ha^{-1} y^{-1} as calculated as described above by the harvest factor (HF). The harvest factor is applied to both harvest machines analysed.

Table 6
The price of labour, diesel and land in the five regions included in our analysis in the year 2004 and 2030 (in € h^{-1} and € l^{-1}). *Sources*: [30–33].

	Labour (€ h^{-1})		Diesel (€ l^{-1})		Land (€ ha^{-1} y^{-1})	
	2004	2030	2004	2030	2004	2030
Poland – Lubelski	4	10	0.70	1.15	50	63
Hungary – Del-Dunantal	5	12	0.89	1.31	45	57
United Kingdom – Devon	23	38	1.22	1.23	201	253
Italy – Lombardia	20	33	0.94	0.95	232	292
Lithuania	3	7	0.68	1.01	10	13

Table 7
The N, P and K application rate in the year 2004 and 2030 (in kg N/P/K ha^{-1} y^{-1}). *Sources*: [35,41,89].

	Miscanthus						Switchgrass					
	2004			2030			2004			2030		
	N	P	K	N	P	K	N	P	K	N	P	K
Poland – Lubelski	58	12	125	80	16	173	92	14	45	128	19	62
Hungary – Del-Dunantal	59	12	127	81	16	176	94	14	45	130	20	63
United Kingdom – Devon	46	9	99	64	13	138	73	11	35	102	15	49
Italy – Lombardia	74	15	159	102	20	221	118	18	57	163	25	79
Lithuania – Lithuania	50	10	107	69	14	149	79	12	38	110	17	53

For miscanthus and switchgrass the optimum N application rate is equal to 1.9 kg N odt^{-1} and 5.0 kg N odt^{-1} [5]. The assumed P and K nutrient content of miscanthus and switchgrass is based on spring harvesting [22,41], whereby the following values are assumed: 0.06% P and 0.65% K for miscanthus [41], 0.09% P and 0.29% K for switchgrass [35].

established using an average of 15 kg ha^{-1} pure live seed and a seed drill and roller [34,35]. The price of seed is 27 € kg^{-1} [36] and is assumed constant to 2030. Miscanthus is reproduced via vegetative propagation. Establishment requires 20000 stems (rhizomes) per hectare and a rhizomes planter and roller [34,36–38]. The price of a rhizome reported in the literature varies from 0.04 € [7] to more than 0.45 € [36]. We estimate the price of rhizomes produced in a greenhouse in 2004 at 0.16 € per piece when bought from a commercial supplier [37]. For the year 2030 we assume that the costs can be decreased to 0.08 € per piece.

2.3.4. Fertilizing

Fertilizer application rates reported in the literature vary widely. Particularly nitrogen fertilizer application rates are uncertain, because there is no consensus on the yield response of miscanthus and switchgrass to nitrogen fertilization. We use the amount of nitrogen (N), phosphorus (P) and potassium (K) removed from the field in the harvested matter as a proxy for the application rate. The rationale is that all nutrients removed from the field need to be replaced to avoid soil mining. The N content on a dry matter basis is 0.3% and 0.6% for miscanthus and switchgrass, respectively and values for P and K are 0.06% P and 0.65% K (miscanthus) and 0.09% P and 0.28% K (switchgrass) [22,35,39–42] Further, the amount of N removed from the field is increased by 43% to account N lost in runoff water, percolation water and N lost through soil erosion and volatisation [39]. In the case of P and K an uptake efficiency of 100% (on the long term) is assumed [39]. The resulting fertilizer application rates are shown in Table 7. Fertilizer prices for the year 2004 are taken from Eurostat [30] and are assumed constant between 2004 and 2030 (data not shown).

2.3.5. Weeding

A generalised herbicide application rate and scheme (for 2004 and 2030) is derived from the literature [34,36], see Tables 3 and 8. Herbicide application is only required during the establishment phase. Further, miscanthus requires a higher herbicide application rate compared to switchgrass, because of later canopy closure and because the costs of establishment and thus also the financial risk of failure of establishment is higher for miscanthus compared to switchgrass and thereby also the need to reduce the risk of failure.

2.3.6. Disease and insect control

Disease and insect control is generally not required [38,43].

2.3.7. Harvesting

Two harvest systems are considered that vary with respect to the economical and environmental performance and the form in which the harvested biomass is delivered:

1. A self-propelled forage harvester that harvests and chops the biomass and than blows the biomass into a trailer and
2. A pull-type harvester-baler that delivers large bales.

Both harvesting systems are presently used for the production of miscanthus in Devon in the United Kingdom, which is the only place in Europe where large-scale, commercial production of herbaceous energy crops currently takes place. The work capacity of harvest machines depends on the yield (see footnote b, Table 5). Existing harvest machines are originally designed for forage harvesting. We assume that the work capacity will increase by an arbitrary chosen 25% as a result of technological improvements and optimisation of harvest systems.

Table 8
Herbicide application rate (kg ha^{-1}; in the establishment year only) and costs (€ kg^{-1} and € ha^{-1}). *Sources*: [34,36].

	Herbicide	Application rate (kg ha^{-1})	Cost (€ kg^{-1})	Total costs (€ ha^{-1})
Miscanthus	Bromosynil/ioxynil/ fluoxypyr	2.0	32	64
	Trifolex-tra	7.7	7.6	59
	Glycophosate	2.5	6.2	16
Switchgrass	Glycophosate	2.5	6.2	16

2.3.8. Storing

Most miscanthus and switchgrass applications require a continuous biomass input for optimal performance. The biomass needs to be stored on the farm for an average of six months. Several storage methods are available:

1. Storage in the open air without covering.
2. Storage in the open air covered with plastic sheeting.
3. Storage in the open air covered with organic material.
4. Storage in existing farm buildings.
5. Storage in new farm buildings.

The cheapest and most used option is storage in the open air with plastic sheeting [4,7,44]. This method is also commonly applied to store silage. Storage in new buildings is prohibitively expensive, unless existing buildings are used, but these (obviously) may not be available [7,45]. Storage in the open air without covering is problematic due to the loss of biomass from decay. Storage in the open air covered with organic material is only attractive when suitable and cheap organic wastes are available, which may not be the case. Data on the capital costs and labour and diesel input of storage in the open air covered with plastic sheeting are shown in Table 9.

2.3.9. Pelletizing

The costs of pelletizing are derived from a detailed study of pelletizing of wood residues in Sweden and Austria in units with 80 and 24 kt pellets per year [46]. The 80 kt facility is considered the most appropriate, because the reduction in pellet production costs outweighs the higher costs resulting from the longer transportation distances from the farm to the pelletizing facility as further discussed in Section 5. For the costs of drying we assume the Austrian case, because the costs of drying in Sweden are very low, because pellet production is combined with a combined heat and power (CHP) plant or biomass district heating plant, which may not be feasible in the region included in our analyses. The costs of pelletizing, excluding labour and energy are 14.5 € t^{-1} pellets [46]. The costs of energy are calculated assuming:

1. An energy requirement for drying of 2.26 MJ kg^{-1} t^{-1} evaporated water.
2. A dryer that uses natural gas and has a drying efficiency of 85% [4]. An electricity demand of 26 kWh_e t^{-1} pellets. Data on the price of electricity in the year 2004 are taken from Eurostat [30].
3. The labour demand is 0.19 h t^{-1} pellets of equivalent labour hours [30,46].

Data on the price of natural gas and electricity in the year 2004 are taken from Eurostat [30]. The price of gas, excluding taxes and transportation, is set at 3.1 € GJ^{-1}, which is assumed to double between 2004 and 2030, following the price of oil [31]. The costs of electricity production, excluding taxes and transportation, in 2004 are 0.05 € kWh_e [47] and an increase of the electricity production costs of 50% is assumed between 2004 and 2030.

2.3.10. Transportation

We assume that the harvested biomass needs to be transported across 100 km, which is sufficient for most biomass processing facilities if:

1. The biomass is derived from a circular production area around the facility.
2. 15% of the agricultural land is used for the production of miscanthus and switchgrass.
3. The total transportation distance is 1.3 times the average distance from within any point of the circular production area to the biomass processing facility that is in the middle [48].

Table 9
The use of labour, tractors (75 kW, see Table 7) diesel fuel and plastic covering material for the storage of chopped and baled miscanthus and switchgrass in the open air covered with plastic sheeting. *Sources*: [4,7,8,45].

	Covering material (€ odt^{-1})	Labour and tractor use (h odt^{-1})	Diesel fuel (l odt^{-1})	Dry matter loss (%)
Chopped	1.6	0.11	1.5	2.0
Baled	3.2	0.04	0.9	3.5

Table 10
Input data used to calculate the costs of (un)loading the biomass from and into a truck and the costs of transportation. *Sources*: [77,49].

	Value	Unit
Transportation		
Fixed costs	0.4	€ km^{-1}
Labour, expressed as equivalent hours of labour in the manufacturing industry	0.8	–
Diesel consumption, empty	0.2	l km^{-1}
Diesel consumption, full	0.4	l km^{-1}
Other variable costs	0.1	€ km^{-1}
Speed	48	km h^{-1}
Maximum load (mass)	27	t
Maximum load (volume)	120	m^3
(Un)loading		
Labour, expressed as equivalent hours of labour in the manufacturing industry	0.09	h tfw^{-1}
Diesel	0.63	l tfw^{-1}
Capital and operation and maintenance	1.30	€ tfw^{-1}

Transportation by truck is the most cost effective option for distances of 100 km or less. Input data are shown in Table 10. The diesel use depends on the mass of the transported biomass. The trucks are assumed to operate at maximum load, whereby the mass and the volume of the biomass can be limiting. Further, it is assumed that no return loads are realised. As data for the (un)loading of biomass, data from European Bulk Services (EBS), which is the largest (un)loader of biomass and agricultural bulk products in the harbour of Rotterdam [49], is used (Table 10). Further assumptions are that the costs of other inputs are assumed constant between 2004 and 2030 and that the costs of unloading are the same as of loading.

3. Environmental impacts of miscanthus and switchgrass production

3.1. Greenhouse gas emissions and primary energy use

The following categories of energy use and GHG emissions are included:

1. The use of energy (diesel, electricity, natural gas) during production, storage, transportation and pelletizing.
2. The direct and indirect emissions of nitrous oxide (N_2O) due to the application of N fertilizers. Direct N_2O emissions are emissions from the field on which the biomass is grown. Indirect emissions are the N_2O emissions from the N that is lost via runoff and leaching and that is emitted elsewhere.
3. The production of fossil energy used during production, storage, transportation and pelletizing.

Table 11
The greenhouse gas emission factors (top table) and primary energy conversion factors (bottom table) used in this study. Numbers between brackets are estimates. *Sources*: see table.

	Direct	Indirect	Total	Unit	Source
Emissions					
Miscanthus rhizomes	0	280	280	$kgCO_2eq.\ ha^{-1}$	[34]
Switchgrass seed	0	8.8	8.8	$kgCO_2eq.\ ha^{-1}$	[34]
Herbicides	0	5408	5408	$gCO_2eq.\ kg^{-1}$	[90]
N fertilizer (production)	0	2329	2329	$gCO_2eq.\ kg^{-1}$	[91]
N fertilizer (nitrous oxide)	4683	1545	6228	$gCO_2eq.\ kg^{-1}$ N	[71,92]
P_2O_5 fertilizer	0	714	714	$gCO_2eq.\ kg^{-1}$ P	[90]
K_2O fertilizers	0	456	456	$gCO_2eq.\ kg^{-1}$ K	[90]
Electricity	0	760	760	$gCO_2eq.\ kWh_e^{-1}$	[90]
Natural gas	56	6	62	$gCO_2eq.\ MJ^{-1}$	[90]
Diesel – agricultural machinery	2740	(904)	3644	$gCO_2eq.\ l^{-1}$	[90,93]
Diesel – truck	2740	(904)	3644	$gCO_2eq.\ l^{-1}$	[90,93]
Diesel – train	2740	(904)	3644	$gCO_2eq.\ l^{-1}$	[90,93]
Diesel – ship	2740	(1808)	4548	$gCO_2eq.\ l^{-1}$	[90,93]
Primary energy use					
Miscanthus rhizomes	0	4000	4000	MJprim ha^{-1}	[34]
Switchgrass seed	0	120	120	MJprim ha^{-1}	[34]
Herbicides	0	188	188	MJprim kg^{-1}	[90]
N fertilizer (production)	0	47	47	MJprim kg^{-1} N	[90]
P_2O_5 fertilizer	0	6.9	6.9	MJprim kg^{-1} P	[90]
K_2O fertilizers	0	7.4	7.4	MJprim kg^{-1} K	[90]
Electricity	3.6	10	13.6	MJprim kWh_e^{-1}	[90]
Natural gas	1.0	0.1	1.1	MJprim MJ^{-1}	[90]
Agricultural machinery – diesel	1.0	(0.3)	1.3	MJprim MJ^{-1}	[93]
Truck – diesel	1.0	0.3	1.3	MJprim MJ^{-1}	[93]
Train – diesel	1.0	0.3	1.3	MJprim MJ^{-1}	[93]
Ship – diesel	1.0	0.7	1.7	MJprim MJ^{-1}	[93]

4. The manufacturing of agricultural inputs (herbicides, fertilizers and planting material).
5. The production, repair and maintenance of agricultural machinery and trucks, trains and ships and also the construction and repair and maintenance of transportation infrastructure (roads, railways, waterways).

The use of energy and agricultural inputs is calculated based on the description of processes and inputs in Section 2. These quantities are multiplied by GHG emission factors and primary energy use factors that are taken from the literature (Table 11). GHG emissions from changes in above- or belowground biomass, soil organic matter and litter due to the conversion of land into energy crop plantations are ignored, because the calculation of these emissions requires an additional set of assumptions on which land use types are replaced and also because data about the GHG emissions from different changes in land use are uncertain. This approach is also commonly applied in existing life cycle studies. Yet, a limited analysis is carried out of the impact of changes in land use on the GHG emissions in Section 5.

3.2. Soil erosion

Soil erosion is the loss of top soil through wind or water. We focus on water erosion, because this is the most common type of erosion in the EU25 [50]. The risk of water erosion is high when there is no or limited soil cover, which is the case after ploughing and harrowing during the establishment of miscanthus and switchgrass. The fast growth of perennial grasses after harvest and the rooting system prevent soil erosion in the second year and onwards. It is assumed that miscanthus and switchgrass is being produced on surplus agricultural land (cropland or pasture). In annual crops the cycle of soil cultivation and establishment is repeated yearly and consequently soil erosion rates are higher compared to perennial crops. Soil erosion rates of pastures are likely comparable or lower, although exact data are lacking.

The relative and absolute soil erosion rates are calculated using the Universal Soil Loss Equation (USLE) [51,52], which is an empirically derived method to calculate water soil erosion rates under various vegetation types.

$$A = RK\,LS\,CP$$

where A = soil loss (in $t\,ha^{-1}\,y^{-1}$). R = rainfall erosion index ($MJ\,mm\,ha^{-1}\,h^{-1}\,y^{-1}$), $R = 0.04830F^{1.610}$ [53], where F is annual rainfall ($mm\,y^{-1}$). Three rainfall levels are included (400, 800 and 1200 $mm\,y^{-1}$) that roughly cover the range in rainfall for the five regions under investigation. K = soil erodibility factor. We calculated the soil erosion rate for medium soils, although light soils also frequently occur in the regions under investigation [54,55]. LS = slope length and slope gradient factor (dimensionless), $LS = (X/22.13)^n(0.065 + 0.045s + 0.0065s^2)$, where X is the slope length (m), which is set at 100 m, s the slope gradient (%), which is set at 4%, and $n = 0.5$ for slopes $\geq 5\%$. C = crop/vegetation and management factor (dimensionless). P = agricultural practice factor (dimensionless; P factor), which is set at 1 (no soil erosion control techniques are assumed).

3.3. Water use

The miscanthus and switchgrass yields assumed in our analysis are based on rain fed conditions. Irrigation is excluded, because of the high costs [56], the risk of depletion of fresh water reservoirs and other forms of environmental degradation (e.g. water logging, salinisation). However, the production of miscanthus and switchgrass can still change the water balance of an area via changes in the evapotranspiration, runoff and percolation compared to the agricultural land that is replaced. This may ultimately lead to adverse hydrological impacts such as reduced aquifer recharge and stream flow that feed reservoirs, wetland, water meadows and other ecosystems. Here a literature review is carried out on the impact of miscanthus and switchgrass production on water resources.

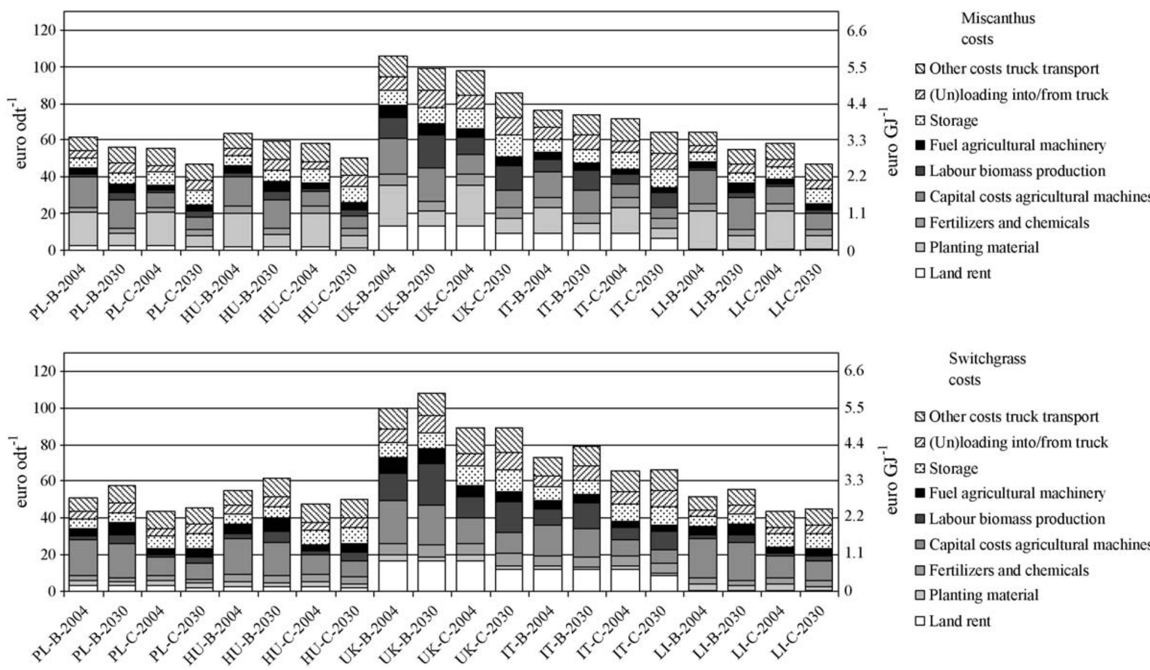

Fig. 1. The costs of production, storage, (un)loading and transport over 100 km of baled and chopped miscanthus (top figure) and switchgrass (bottom figure) in the years 2004 and 2030. PL: Poland – Lubelski; HU: Hungary – Del-Dunantal; UK: United Kingdom – Devon; IT: Italy – Lombardia; LI: Lithuania; B: baled biomass; C: chopped biomass.

3.4. Biodiversity

In this study the focus is on changes in the diversity of species of flora and fauna in miscanthus and switchgrass fields compared to the agricultural production system that is replaced. In this study results and conclusions from the literature are summarised.

4. Results

4.1. Economic performance

Fig. 1 shows the costs of production, storage, (un)loading and transportation over 100 km by truck of baled and chopped miscanthus and switchgrass in the regions under investigation in the year 2004 and 2030.

The costs of production and storage of miscanthus in the year 2004 are calculated to be 43–87 € odt^{-1} (or 2.3–4.8 € GJ$_{HHV}$$^{-1}$), dependent on the yield and price of inputs (labour, land, diesel) in the five regions that are investigated. The costs of switchgrass are estimated to be 30–81 € odt^{-1} (1.6–4.4 € GJ^{-1}). Miscanthus is more expensive than switchgrass, because of the higher costs of planting material. Miscanthus rhizomes cost 3200 € ha^{-1} compared to 540 € ha^{-1} for switchgrass seed. The higher costs of planting material are only partially compensated by the 25% higher yield of miscanthus compared to switchgrass. In the year 2004, miscanthus is on average 24% more expensive than switchgrass, measured across the lifetime of the plantation.

The costs of production and storage of miscanthus and switchgrass are expected to change between 2004 and 2030 due to increasing yields per hectare, the increase of the input costs (land, labour and fuel), the increasing capacities of harvest machines and the reduction of the costs of miscanthus rhizomes. The net effect is a decrease of the costs of production and storage of miscanthus between 2004 and 2030 (−15% to −27%), while the costs of switchgrass are expected to remain roughly constant (−3% to 7%). Another outcome is that in 2030 the costs of miscanthus production and storage are comparable to those of switchgrass.

The costs of transporting the biomass over 100 km by truck (including (un)loading) are calculated to be 11–18 € odt^{-1} (0.6–1.0 € GJ^{-1}) in the case of baled and 13–20 € odt^{-1} (0.7–1.1 € GJ^{-1}) in the case of chopped material. Transportation of chopped biomass is more expensive, due to the lower density of chopped compared to baled biomass (0.12 t m^{-3} and 0.15 t m^{-3}, respectively). The costs are higher in Italy and the United Kingdom compared to Poland, Hungary and Lithuania, because the labour costs in Italy and the United Kingdom are higher compared to the other three countries. The costs of transportation are expected to increase by 8–31% between 2004 and 2030 due to the increase of the price of labour and fuel. Particularly the labour costs in East Europe are expected to increase rapidly, although the labour costs in the year 2030 are still significantly below the levels found in the Italy and the United Kingdom. Fig. 1 also shows that the total costs of production, storage, (un)loading and transportation of chopped biomass are 6–15% lower compared to baled biomass.

The costs of pelletizing are shown in Fig. 2.

The costs of pelletizing are 26–29 € odt^{-1} (1.4–1.6 € GJ^{-1}) in 2004 and 31–36 € odt^{-1} (1.7–2.0 € GJ^{-1}) in 2030. The capital costs are the same in all regions, so differences in the total costs are

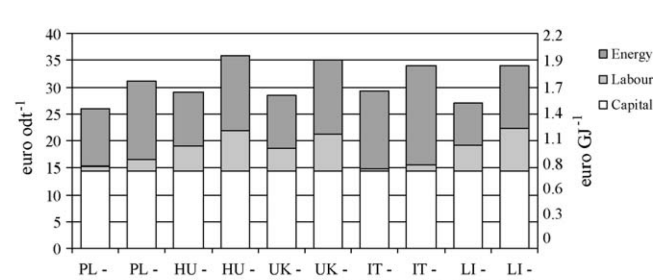

Fig. 2. The costs of pelletizing miscanthus or switchgrass in the year 2004 and 2030 (excluding feedstock costs). PL: Poland – Lubelski; HU: Hungary – Del-Dunantal; UK: United Kingdom – Devon; IT: Italy – Lombardia; LI: Lithuania. *Source*: [30,46] plus corrections for differences in the price of energy and labour using country-specific data. Italy 2004 look to me like too low labour costs.

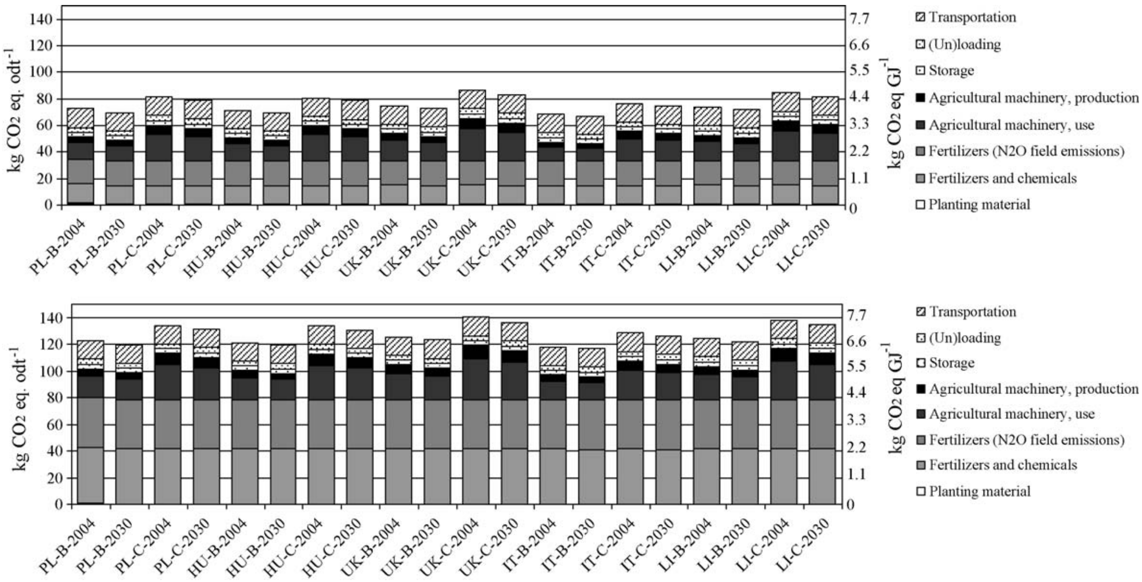

Fig. 3. The greenhouse gas emissions of production, storage, (un)loading and transport over 100 km of baled and chopped miscanthus (top figure) and switchgrass (bottom figure) in the years 2004 and 2030. P: production; PL: Poland – Lubelski; HU: Hungary – Del-Dunantal; UK: United Kingdom – Devon; IT: Italy – Lombardia; LI: Lithuania; B: baled; C: chopped.

caused by variations in the price of labour, natural gas and electricity. Comparison of Figs. 1 and 2 shows that the costs of pelletizing are higher than the costs of transportation, which means that pelletizing is not an effective strategy to reduce the costs of transportation. However, it should be noted that the costs of pelletizing are sensitive to assumptions on the moisture content and the price of natural gas and electricity used for pelletizing.

4.2. Environmental performance

Fig. 3 shows the GHG emissions of the production, storage, (un)loading and transportation over 100 km of baled and chopped miscanthus in the years 2004 and 2030. The GHG emissions in the case of miscanthus are estimated to be 69–86 kg carbon dioxide equivalents (CO_2 eq.) odt^{-1} (3.8–4.7 kg CO_2 eq. GJ^{-1}) in 2004, values for switchgrass are 118–140 kg CO_2 eq. odt^{-1} (6.4–7.7 kg CO_2 eq. GJ^{-1}). The emissions are projected to decrease as a result of higher crop yields to 67–83 kg CO_2 eq. odt^{-1} (3.7–4.5 kg CO_2 eq. GJ^{-1}) in 2030 in the case of miscanthus and 117–137 kg CO_2 eq. odt^{-1} (6.4–7.5 kg CO_2 eq. GJ^{-1}) in the case of switchgrass. The decrease in emissions is less than one would expect based on the increase in yields, because the fertilizer application rate is linearly dependent on the yield. This also explains why the differences in emissions between regions are so limited. The emissions are far below the emissions of fossil energy carriers, which are for liquid fossil fuels (gasoline, diesel, fuel oil), natural gas and coal circa 83, 60 and 101 kg CO_2 eq. GJ^{-1}, respectively.

The four most important GHG emission categories are emissions from the production of fertilizers. N_2O emissions as a consequence of N fertilizer application and emissions due to the use of diesel by agricultural machinery and trucks. Truck transport contributes up to 20% of the total emissions. The emissions of chopped biomass are higher compared to baled biomass, because of the high fuel use of the self-propelled forage harvester chopping the biomass. Differences between the regions investigated are limited, because the crop management is assumed the same in all regions and because the emissions from storage, (un)loading and transport are also fixed per tonne.

We also calculated the use of primary energy for the production, storage and transportation of miscanthus and switchgrass. The ratio bioenergy output to fossil primary energy input ratio is 23–40 in the case of miscanthus in the year 2004 and 32–56 in the year 2030. For switchgrass these values are 25–47 and 27–49 for 2004 and 2030, respectively. The variability in the primary energy balance is mainly the result of differences in the fertilizer application rate. These data indicate that the use of miscanthus or switchgrass for the replacement of fossil fuels could be an efficient way of reducing fossil fuel use.

We also investigated the GHG emissions and primary energy use of pelletizing. The GHG emissions of pelletizing are assumed to be independent of the region and are calculated at 89 gCO_2 eq. odt^{-1} of which 69 gCO_2 eq. odt^{-1} is from the use of natural gas and 19 gCO_2 eq. odt^{-1} is from the use of electricity. The primary energy use is calculated at 1.6 GJ odt^{-1}, which is equal to 9% of the energy content of the biomass. These results show that pelletizing is disadvantageous, because of the high GHG emissions and primary energy use.

4.2.1. Soil erosion

Several studies indicate that water induced soil erosion will be reduced, particularly when miscanthus or switchgrass replace conventional annual crops. Jankauskas and Jankauskiene [57] measured erosion rates during long-term field experiments. Winter rye was found to have a soil erosion rate of 5.4–17 t^{-1} ha^{-1} y^{-1}, spring barley 18–63 t^{-1} ha^{-1} y^{-1} and potatoes 44–186 t^{-1} ha^{-1} y^{-1}, while perennial grasses reduce erosion to zero. Bical Energy [58] reports a reduction of the rate of soil erosion from 11 t ha^{-1} y^{-1} to 1 t ha^{-1} y^{-1} when cereals are replaced by perennial grasses and from 22 t ha^{-1} y^{-1} to 0.2 t ha^{-1} y^{-1} when maize is converted. Therefore, the US Conservation Reserve Progamme uses perennial grasses to minimize soil erosion [59,60]. These observations are in line with the soil erosion prevention guidelines of the British Department for Environment, Food and Rural Affairs [61], in which miscanthus production is classified as a moderately susceptible land use type that can be carried out at areas with a high and very high risk of soil erosion.

Table 12 shows the crop or vegetation factor as well as the soil erosion rates calculated for various vegetation types. The variation in annual precipitation in Lubeleski (Poland), Del-Dunantal (Hungary) and in Lithuania is in the 400–800 mm y^{-1} range. The

Table 12
Soil erosion rates (t^{-1} ha^{-1} y^{-1}) and the crop/vegetation factor (C-factor) for various land use types and for three levels of rainfall. *Sources*: [39,51,52,94–96].

	C-factor	Soil erosion rate (in t^{-1} ha^{-1} y^{-1})		
		400 mm y^{-1}	800 mm y^{-1}	1200 mm y^{-1}
Roads and other bare areas	1.000	26.3	80.1	154.5
Fresh clean-tilled seedbed	0.800	21.0	64.1	123.6
Silage corn, beans, canola	0.500	13.1	40.1	77.2
Grain corn	0.400	10.5	32.1	61.8
Cereals (spring or winter)	0.350	9.2	28.0	54.1
→Miscanthus, switchgrass	0.100	2.6	8.0	15.4
Grassland	0.050	1.3	4.0	7.7
Deciduous forest	0.009	0.2	0.7	1.4
Mixed forest	0.007	0.2	0.6	1.1
Evergreen/coniferous forest	0.004	0.1	0.3	0.6
Forest/woody wetland	0.003	0.1	0.2	0.5

annual precipitation in the Devon (the United Kingdom) and Lombardia (Italy) is 800 mm y^{-1} or above. The results presented in Table 12 are shown to indicate the order of magnitude of soil erosion and to show differences in soil erosion rate between vegetation and crop types. More accurate and site-specific data are required on rainfall intensity, slope length, slope gradient and on the crop, vegetation and agricultural practice factor to generate more reliable results.

There is no generally accepted set of maximum tolerable and realistically achievable soil erosion rates, because this depends on the local physical and socio-economic conditions (e.g. soil depth, the impact on crop production costs). However, the results show that the conversion of conventional crops (e.g. cereals and maize) to miscanthus and switchgrass reduces soil erosion roughly by two-third or more. The conversion of pastures increases soil erosion rates roughly by a factor two. The net impact could not be calculated, due to a lack of region-specific data on the areas of arable land and pastures potentially available for energy crop production.

4.2.2. Water use

The water use efficiency, which is defined as the dry matter production of harvestable product per water loss, of C_4 plants (e.g. miscanthus, switchgrass, sugar cane, maize) is typically twice that of C_3 plants (most plants are C_3 plants, including wheat, barley, sugar beet, sunflower, potatoes, all trees) [62]. However, the focus in this paper is more on the hydrological impacts, whereby the total water use is more important than the water use efficiency. Most studies indicate that, because of the fast growth, large leave area and deep rooting system, the rate of evapotranspiration of energy grasses is higher compared to traditional annual crops [56,63]. Also the interception of rainfall is higher compared to annual crops [63]. As a result, the deep percolation and runoff of water from areas under energy grass cultivation is reduced compared to annual crops. Calculations done for four sites in the United Kingdom showed a decrease of the amount of hydrological effective rainfall (HER; which is defined as percolation plus runoff) of 50–60% compared to annual crops [63]. The reduced percolation and runoff to groundwater reservoirs, streams and rivers may lead to a depletion of these water bodies. This is particularly relevant considering the typically deep rooting systems of energy grasses (2–3 m deep on suitable soils) that allow energy grasses to avoid or reduce water stress during periods of limited rainfall and thus allow for optimum growth and high yields. The Centre for Ecology and Hydrology (CEH) of the United Kingdom specifically mentions Devon as one of the regions in the United Kingdom where large scale production of grasses in catchment areas should be avoided [56]. The reason is that additional pressures on scarce surface water reservoirs, which are the main sources of water in Devon, should be avoided. This is particularly relevant during the summer, when the population increases greatly through holiday visitors. Further, the Guidelines for growing Short Rotation Coppice (SRC), which are published by the CEH, state that SRC plantations should be located in areas where rainfall is at least 600 mm y^{-1} [64]. The water requirements of energy grasses such as miscanthus is likely similar or slightly below that of SRC [56,63]. For comparison: in Lubeleski (Poland), Del-Dunantal (Hungary) and in Lithuania the average rainfall is 400–800 mm y^{-1}, the rainfall in the Devon and Lombardia (Italy) is above 600 mm y^{-1}. The CEH also concluded that effects at the level of catchment areas are negligible, provided that extensive areas of single catchments are not planted. Further, large differences between cultivars in water use efficiency have been observed [65]. Breeding and cultivar selection may thus also help to avoid negative impacts. An advantage of the high water use of energy grasses is that they may be used to reduce peak flows and thereby reduce the risks of local flooding. This goes particularly for switchgrass, which is more tolerant to flooding than miscanthus [66]. The results presented above indicate that the impact of perennial grasses on fresh water reservoirs is likely limited, provided that large monocultures in single catchment areas or areas with low water availability are avoided.

4.2.3. Biodiversity

Several studies show that the biodiversity in miscanthus and switchgrass fields is generally higher compared to conventional annual crops. For example, Semere and Slater [18] found that the ground flora diversity in miscanthus fields is higher during the first three years after establishment compared to conventional cash crops. The initial slow growth and the wide spaces between rows of miscanthus leave sufficient sunlight and nutrients for the growth of weed. Yet, after the first three years the canopy closes and the flora diversity in miscanthus fields decreases [67]. Positive impacts on the spiders, beetles and earthworms diversity have also been observed in the case of the replacement rye with miscanthus [43]. Further, according to Börjesson [29] the diversity of soil micro-organisms and soil fauna in energy grass cultivation is higher compared to annual crops. This goes particularly for decomposers such as earthworms, harvest men and carbides, because of the reduced soil tillage, lower use of agrochemicals and increased litter layer. Eppel-Hotz and Jodl [68] reported a higher number of mammal, bird, beetle and spider species in miscanthus fields in comparison to corn.

In general, the higher species diversity in perennial grasses compared to annual crops is the result of the higher number of ecological niches in fields with perennial grasses compared to annual crops [4,69] and also the lower level of soil disturbance, the lower use of pesticides and herbicides compared to annual crops

and also the harvest in autumns provides shelter to animals during winter. Perennial grasses contain niches that are common to scrubland and forests and that attract certain small mammal and bird species, while the empty spaces between the rows with leaf litter provide a habitat for among others certain species of small mammals and flora [69]. Further, Semere and Slater [18] also found that the species diversity of ground flora, small mammals and birds is higher in the borders of the field compared to the middle. Roth et al. [20] show that the harvesting schedule is also important for the biodiversity within fields on which switchgrass is grown. An irregular harvest pattern provides habitat for a larger number of bird species than if all fields were harvested simultaneously.

We conclude that the biodiversity of perennial grasses can be increased by optimizing the size of the field and by locating the fields close to different types of vegetation and by differentiating the harvesting schedule. A proportion of 10–20% energy forest in open farmland has been estimated to be optimal for flora and fauna diversity [29]. This conclusion probably also holds for perennial grasses. The 10–20% fraction is also broadly in line with the fraction of agricultural land that is available for energy crop production in the year 2010 and 2030 in the five regions considered (Table 1).

5. Discussion

5.1. Sensitivity analysis

Various assumptions are made when calculating the costs and GHG emissions of miscanthus and switchgrass supply chains. A sensitivity analysis is carried out in which the impact of the most important assumptions on the results is evaluated to understand the robustness of our results and to identify the variables and uncertainties that can be targets for future research and policy making. No sensitivity is carried out for the energy balance, because of the high and robust bioenergy output to fossil energy input ratio. The data included in the sensitivity analysis and the rationale is presented below. The results are summarised in Table 13.

5.1.1. Yield

The combined effect of two uncertainties is investigated. First, the uncertainties of the yields predicted by MiscanMod for the year 2004 are calculated at ±20% by comparing modelled yields with field measurements [70]. In addition the uncertainties of the growth of yields between 2004 and 2030 are investigated assuming a yield growth of 1.0–2.0% y^{-1} (see Section 2.2). Thus, the total uncertainty in the year 2004 is set at ±20% and in the year 2030 at −27% and +31%.

5.1.2. Land rent

The combined effect of two uncertainties is analysed. First, data on land rent are based on the price of cropland that is classified as suitable, whereby we include data on areas that are classified as moderately suitable and as very suitable as a proxy for the uncertainties of the data on the land rent in the year 2004. Second, the uncertainties related to changes in land use between 2004 and 2030 are included, following the two scenarios proposed by De Wit et al. [33]:

1. The price of land remains constant per hectare at the 2004 level in both West and East Europe.
2. The price of land in West Europe remains constant per hectare at the 2004 level and the price of land in East Europe converges to the level in West Europe, but with a maximum of 208 € ha^{-1} y^{-1}, which is the land price in the United Kingdom.

The following data are included, whereby three values are given for each country, namely the minimum land rent in the year 2004, the default land rent in 2004, the maximum in 2004, the minimum in 2030, the default in 2030 and the maximum in 2030: Poland 28–50–72–28–63–208 € ha^{-1}, Hungary 25–45–65–25–57–208 € ha^{-1}, United Kingdom 194–201–208–253–194–208 € ha^{-1}, Italy 155–232–309–155–292–309 € ha^{-1}, Lithuania 5–10–14–13–5–69 € ha^{-1}. Note that the maximum value calculated for the year 2030 is not necessarily higher than the default.

5.1.3. Rhizome costs

In the sensitivity analysis a price of 0.10 € per piece for the year 2004 is assumed, which is roughly the lowest level found in the literature and a price of 0.16 € per rhizome in 2030 is considered, assuming that the price of rhizomes does not change between 2004 and 2030 [35,42].

5.1.4. Fertilizer application rates

Fertilizer application rates reported in the literature vary widely. Particularly the application rates of N fertilizer are uncertain, because there is no consensus on the yield response of miscanthus and switchgrass to N fertilization. In the sensitivity analysis we include the following ranges in nutrient content (on dry matter basis): 0.12–0.64% N for miscanthus, 0.37–1.10% N for switchgrass. For P and K the following ranges are considered: 0.02–0.10% P and 0.41–0.90% K (miscanthus), 0.06–0.11% P and 0.13–0.44% K (switchgrass) [35,42].

5.1.5. GHG emissions from changes in land use

The impact of GHG emissions from changes in land use is investigated by considering two 'reference land use systems' or

Table 13
The sensitivity of the results for changes in the most important assumptions.

Parameter	Impact on the costs (%)	Impact on the GHG emissions (%)
Land rent maximum 2004 and 2030 (UK and IT)	0 to 6	n/a
Land rent maximum 2004 and 2030 (PL, HU and LT)	0 to 12	n/a
Land rent minimum 2004 and 2030 (UK and IT)	−0 to −6	n/a
Land rent maximum 2004 and 2030 (PL, HU and LT)	−1 to −6	n/a
Yield minimum 2004 and 2030	10 to 7	3 to 9
Yield maximum 2004 and 2030	−12 to −7	−2 to −6
Rhizome price minimum 2004	−7 to −14	n/a
Rhizome price maximum 2030	7 to 16	n/a
Fertilizers minimum 2004 and 2030	−1 to −4	−21 to −27
Fertilizers maximum 2004 and 2030	2 to 4	38 to 57
Emissions from changes in land use; cropland as reference; 2004 and 2030	n/a	118 to 309
Emissions from changes in land use; pasture as reference; 2004 and 2030	n/a	−382 to −1091
Transportation distance 50 km 2004 and 2030	−5 to −10	−6 to −10
Transportation distance 200 km 2004 and 2030	10 to 21	10 to 21

'reference systems', namely cropland and pastures, see also Table 1. Two types of emissions are included.

1. *N_2O emissions*: We assume that 1% of the N in fertilizers is released as N_2O–N [71], see Table 11. This emission factor represents the fertilizer induced emissions (FIE), which are defined as the difference in emissions between a fertilized and an unfertilized field. However, the direct emissions can be higher or lower than the FIE, dependent on the type of vegetation that is replaced [72]. For cropland and pastures a 0.1% and 1.2% emission factor are included, which are the emission factors for crops (maize, wheat, sugar beet and rapeseed) produced in Europe and in the US and that are used for the production of first-generation biofuels in the case of conventional crops and pastures are replaced, respectively [72]
2. *Other GHG emissions from land conversion*: Delucchi and Lipman [73] carried out a review of the literature about this subject and they concluded that the conversion of cropland and temperate grassland to perennial grasses changes the carbon content of the above- or belowground biomass, soil organic matter and litter by 2 kg C m^{-2} and −7 kg C m^{-2}, respectively. The emissions are discounted over a period of 20 years, following [71].

5.1.6. Transportation distance

In this sensitivity analysis we estimate the impact of the haulage distance on the costs and GHG emissions, assuming an arbitrary chosen bandwidth of 50 km and 200 km.

The results of the sensitivity analysis show that the crop yields, the price of rhizomes and the transportation distance can change the costs of production, storage and transportation by −12% to 21%, but the combined impact is even larger. Further, the impact of uncertainties on the GHG emissions is also substantial. Particularly the fertilizer application rates and the emissions from changes in land use are uncertain and have a large impact on the GHG emissions. However, it should be noted that data about N_2O emissions and other GHG emissions that are included in the sensitivity analysis are highly uncertain, because field measurements involving perennial grasses are almost not available. Based on the sporadic data that are available, we calculated the total emissions in the case that pastures are replaced by miscanthus and switchgrass at 11–22 kg CO_2 eq. GJ^{-1}, which is still well below the emissions of fossil energy carriers: the emissions of liquid fossil fuels (gasoline, diesel, fuel oil), natural gas and coal are circa 83, 60 and 101 kg CO_2 eq. GJ^{-1}, respectively. However, one could also argue that natural vegetation is the most appropriate type of reference land use, assuming that, in the absence of bioenergy production, all surplus cropland and pastures would be converted into natural vegetation, as has been the case in Europe during the previous decades [74]. Natural vegetation, and particularly forests, typically have a high above- or belowground biomass, soil organic matter and litter content compared to cropland and pastures. If the reduction of carbon sequestration is allocated to switchgrass and miscanthus, then the total GHG emissions increase to 44–118 kg CO_2 eq. GJ^{-1}, which are in the same order of magnitude as those of fossil fuels. Also the performance with respect other environmental parameters that are investigated in this study (soil erosion, water use and biodiversity) will be negative, assuming that natural vegetation, by definition, is the type of vegetation with the best performance.

5.2. Comparison with other studies

The results of our calculations are compared with estimates found in the literature. Differences in outcomes can be explained by differences in assumptions. For example, Huisman et al. [7,8] calculated the total costs of various miscanthus production chains in the Netherlands at circa 120–130 € odt^{-1}, compared to 94 € odt^{-1} when our calculations are carried out for the Netherlands. The main reasons for these differences are the lower yield (12 odt ha^{-1} y^{-1} vs. 16 odt ha^{-1} y^{-1}) and higher price of land (725 € ha^{-1} y^{-1} vs. 333 € ha^{-1} y^{-1}) assumed by Huisman et al. [7,8]. In another study the production costs of switchgrass in the United Kingdom and Italy are estimated at 31 € odt^{-1} and 30 € odt^{-1}, respectively [35]. According to our calculations the costs of miscanthus production are 51–79 € odt^{-1} in the United Kingdom and 36–53 € odt^{-1} in Italy. Key differences are the costs of fertilizers, agro-chemicals, labour, the interest rate and the methodology used to calculate the costs. Kumar and Sokhansanj [75] calculated the costs of harvesting and storage of switchgrass at circa 18 € odt^{-1} and 11 € odt^{-1} for baled and chopped biomass, respectively (excluding the costs of labour). These values are comparable to our results of 17–25 € odt^{-1} for baled and 11–17 € odt^{-1} for chopped switchgrass. The lower costs of baled compared to chopped biomass are confirmed by Huisman et al. [7,8].

Also the costs of road transport are in line with data found in the literature. Differences are due to different assumptions on the density of the transported biomass, on the availability of cargo on the way back, and on the costs of unloading [7,8,38,75,76]. For example, Bullard and Nixon [38] calculated the costs of transportation to be 0.44–0.74 € odt^{-1} for transportation across 40–80 km. These costs are equal to 0.29–0.48 € odt^{-1} after correction for differences in assumptions. We estimated the costs to be 0.37–0.48 € odt^{-1}, including (un)loading. The costs of rail transport differ from data found in the literature as a result of differences in the original data sources. For example, one source estimates the costs of rail transport in the Netherlands at 0.015–0.035 € tkm^{-1} dependent on the type of cargo [77], while an other source reports a price of 0.055–0.068 € tkm^{-1} in the Netherlands [78]. Our estimates of the GHG and primary energy use are in line with the ranges found in the literature. For example, estimates of the GHG emissions vary between 75 kg CO_2 eq. odt^{-1} and 295 kg CO_2 eq. odt^{-1} [75,79]. Differences with our results are caused mainly by differences in system boundaries, the fertilizer application rate, yield and transportation distance. Detailed data on pelletizing are scarce and results vary widely. For example, Hamelinck et al. [76] calculated the costs of pelletizing forestry residues at circa 17 € odt^{-1} or 1.0 € GJ^{-1}. These lower values are the result of the lower costs of capital and lower price of fuel used for drying the biomass compared to the values assumed in our analysis.

6. Conclusions

The costs of producing, storing and transporting across 100 km (which is sufficient for most biomass applications) of miscanthus are lower than for switchgrass in the year 2004, namely 55–106 € odt^{-1} or 3.0–5.8 € GJ^{-1} for miscanthus and 43–100 € odt^{-1} or 2.3–5.5 € GJ^{-1} in the case of switchgrass. The costs of miscanthus are projected to decrease between 2004 and 2030 to 47–99 € odt^{-1} (2.6–5.4 € GJ^{-1}) as a result of the assumed increase of the yield and due to the decrease of the costs of the planting material. The costs of switchgrass are estimated to remain roughly stable at the 2004 level (46–108 € odt^{-1} or 2.5–5.9 € GJ^{-1}), because the increase in yield is counteracted by the increase of the price of land, labour and fuel. Further, it can be concluded that chopped biomass is cheaper than baled biomass, although the difference is limited.

The lowest costs of production, storage and transportation were found for Poland, followed by Hungary and Lithuania. For these regions a cost range of 43–64 € odt^{-1} (2.3–3.5 € GJ^{-1}) was calculated for the year 2004. This is an attractive range compared

to the price of crude oil and natural gas in 2004, which was 3.1 and 4.6 € GJ^{-1}, respectively, excluding taxes and transportation costs, but this is higher than costs of coal in 2004, which was ca. 1.7 € GJ^{-1}. The costs in 2004 are higher in Italy and the United Kingdom, namely 66–106 € odt^{-1} or 3.6–5.8 € GJ^{-1}. The difference between the regions is caused by differences between the price of labour, fuel, land and between the yields. The costs of miscanthus and switchgrass are projected to remain constant between 2004 and 2030, so the doubling of the price of crude oil and natural gas projected between 2004 and 2030 will make miscanthus and switchgrass even more competitive. Yet, miscanthus and switchgrass are currently not competitive with coal and will also not become competitive. However, these calculations exclude the impact of GHG mitigation credits, which might improve the relative competitiveness of the different applications during the coming decades, but this will be analysed in detail in a separate article [80]. Key uncertainties for the economic performance are the price of the rhizomes, the price of land and the crop yield. However, even when, for example, a 50% increase of the costs is considered, than the costs of production, storage and transportation in Poland, Hungary and Lithuania are still within an attractive range (3.5–5.2 € GJ^{-1}) compared to the price of crude oil and natural gas in 2004 (3.1 and 4.6 € GJ^{-1}, respectively, excluding taxes and transportation costs). Key uncertainties and targets for future research and optimisation of supply chains are the price of the rhizomes, the price of land and the crop yield.

The GHG emissions of production, storage and transportation of miscanthus are estimated at 69–86 kg CO_2 eq. odt^{-1} (3.8–4.7 kg CO_2 eq. GJ^{-1}) in 2004 and these are projected to decrease to 67–83 kg CO_2 eq. odt^{-1} (3.7–4.5 kg CO_2 eq. GJ^{-1}). The emissions from switchgrass biomass are 118–140 kg CO_2 eq. odt^{-1} (6.4–7.7 kg CO_2 eq. GJ^{-1}) in 2004 and 117–137 kg CO_2 eq. odt^{-1} (6.4–7.5 kg CO_2 eq. GJ^{-1}) in 2030. Differences between the GHG emissions of miscanthus produced in different regions are limited, because the emissions and energy use from the production and use of fertilizers and agricultural machinery are assumed to be (almost) fixed per tonne biomass. These emissions are well above the GHG emissions of oil products (gasoline, diesel, fuel oil), natural gas and coal, which are ca. 83, 60 and 101 kg CO_2 eq. GJ^{-1}, respectively.

Further, the ratio bioenergy output to fossil primary energy input ratio is calculated at 23–40 in the case of miscanthus in the year 2004 and 32–56 in 2030. For switchgrass these values are 25–47 and 27–49 for 2004 and 2030, respectively. These results indicate that the replacement of fossil fuels by perennial grasses can be a robust, promising strategy to curb GHG emissions and to reduce the use of fossil fuels. However, key uncertainties when calculating the GHG emissions from miscanthus and switchgrass production are the fertilizer application rate, the transportation distance, and particularly the emissions from the alternative land use form, which could be realised. The use of abandoned agricultural land for bioenergy crop production could reduce the conversion of abandoned agricultural land to forest in the EU and thus reduce carbon sequestration (the forest area in the EU25 is increasing at the expense of agricultural land). On the other hand, the replacement of annual crops by energy grasses can have a positive carbon sequestration effect.

A key advantage of miscanthus and switchgrass, but also of other perennial crops, is the combination of a relatively high yield (and thereby high potential) with a relatively low environmental pressure compared to annual crops. Literature analysis showed a decrease in the rate of soil erosion compared to conventional annual crops, but an increase compared to permanent pastures. The impacts on biodiversity are mixed. Positive effects are recorded for many species when annual crop production is replaced. A crucial aspect seems to be the range in niches that miscanthus and switchgrass provide (forest, scrubland, and cropland). Ensuring high habitat diversity is therefore a key target for crop management and the planning of the location of plantations. The location of plantations in the vicinity of a diverse range of other vegetation patterns, ensuring the presence of full-grown unharvested fields that provide a habitat for particularly bird species, but also the avoidance of large fields or monoculture are potentially promising strategies. 10–20% of the area of open farmland has been suggested as an optimum. The size and location of plantations is also important to avoid negative impacts on fresh water reservoirs due to the high total water consumption of energy grasses compared to annual crops. The planting of large areas should be avoided and also areas close to water ways or where groundwater tables are high, particularly within a single catchment and in areas with limited rainfall ($\ll$600 mm y^{-1}). Also the selection of cultivars with high water use efficiency may avoid negative impacts.

In 2007 a proposal of the European Commission was accepted that includes a target that 20% the total primary energy consumption in 2020 should come from renewable sources, whereby bioenergy is expected to play an important role [2]. The total potential of perennial crops in the EU25, taking into account the demand for land for other purposes and environmental criteria, has been calculated at circa 8% of the primary energy use in 2030 [81]. We conclude that miscanthus and switchgrass are two promising bioenergy crops, mainly because of the relatively high yield, the relatively extensive (low-cost) production system and consequently the relatively low production costs. Another key advantage is the relatively low environmental pressure, when compared to conventional crops, whereby the overall environmental impacts of switchgrass and miscanthus production depend on the type reference land use. Therefore, we conclude that miscanthus and switchgrass are promising energy crops that may contribute to the realisation of this goal.

Acknowledgements

This study is part of the European Non Food Agriculture (ENFA) project, which aims at analysing the economic and environmental performance of non-food agricultural products. The ENFA project is funded by the EU. We thank Dr. P.J. Stampfl (Trinity College, Dublin, Ireland) for calculating the yields of miscanthus and Prof. Dr. W.C. Turkenburg (Utrecht University, the Netherlands) for his comments and suggestions. Also many thanks to P. Carver of BICAL Biomass Industrial Crops for supplying data on the cultivating miscanthus.

References

[1] EC. Green Paper. Towards a European strategy for the security of energy supply. Brussels, Belgium: European Commission (EC), Directorate-General for Energy and Transport; 2001. p. 111.
[2] EC. Renewable Energy Road Map. Renewable energies in the 21st century: building a more sustainable future. Brussels, Belgium: European Commission (EC); 2007. p. 20.
[3] EC. Proposal for a Directive of the European Parliament and of the Council on the promoting of the use of energy from renewable sources. Brussels, Belgium: European Commission (EC); 2008. p. 63.
[4] Jones M, Walsh M. The Miscanthus Handbook. London, United Kingdom: Food Agro Industry Research (FAIR) programme of the EU, James & James; 2000.
[5] Boehmel C, Lewandowski I, Claupein W. Comparing annual and perennial energy cropping systems with different management intensities. Agricult Syst 2007.
[6] Cappelletto P, Mongardini F, Barberi B, Sannibale M, Brizzi M, Pignatelli V. Papermaking pulps from the fibrous fraction of Miscanthus × Giganteus. Ind Crops Products 2000;11:205–10.
[7] Huisman W, Venturi P, Molenaar J. Costs of supply chains of Miscanthus giganteus. Ind Crops Products 1997;6:353–66.

[8] Huisman W, Venturi P, Molenaar J. Cost calculations of production chains of Miscanthus giganteus. Wageningen, the Netherlands: Wageningen Agricultural University; 1997. p. 45 plus Appendixes.
[9] Heaton EA, Long SP, Voigt TB, Jones MB, Clifton-Brown J. Miscanthus for renewable energy generation: European Union experience and projections for Illinois. Mitigat Adapt Strategies Global Change 2004;9:433–51.
[10] Nelson RG, Ascough II JC, Langmeier MR. Environmental and economic analysis of switchgrass production for water quality improvement in northeast Kansas. J Environ Manage 2006;79:336–47.
[11] Styles D, Jones MB. Current and future financial competitiveness of electricity and heat from energy crops: a case study from Ireland. Energy Policy 2007;35:4355–67.
[12] Monti A, Fazio S, Lychnaras V, Soldatos P, Venturi G. A full economic analysis of switchgrass under different scenarios in Italy estimated by BEE model. Biomass Bioenergy 2007;31:177–85.
[13] Kahle P, Beuch S, Boelcke B, Leinweber P, Schulten H-R. Cropping of Miscanthus in Central Europe: biomass production and influence on nutrients and soil organic matter. Eur J Agronomy 2001;15:171–84.
[14] Lewandowski I, Schmidt U. Nitrogen, energy and land use efficiencies of miscanthus, reed canary grass and triticale as determined by the boundary line approach. Agricult Ecosyst Environ 2006;112:335–46.
[15] Zan CS, Fyles JW, Girouard P, Samson RA. Carbon sequestration in perennial bioenergy, annual corn and uncultivated systems in southern Quebec. Agricult Ecosyst Environ 2001;86:135–44.
[16] Styles D, Jones MB. Energy crops in Ireland: quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity. Biomass Bioenergy 2007;31:759–72.
[17] Rowe RL, Street NR, Taylor G. Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK. Renew Sustain Energy Rev 2009;13(1):271–90.
[18] Semere T, Slater FM. Ground flora, small mammal and bird species diversity in miscanthus (Miscanthus $\times$ giganteus) and reed canary-grass (Phalaris arundinacea) fields. Biomass and Bioenergy 2007;31:20–9.
[19] Semere T, Slater FM. Invertebrate populations in miscanthus (Miscanthus $\times$ giganteus) and reed canary-grass (Phalaris arundinacea) fields. Biomass Bioenergy 2007;31:30–9.
[20] Roth AM, Sample DW, Ribic CA, Paine L, Undersander DJ, Bartelt GA. Grassland bird response to harvesting switchgrass as a biomass energy crop. Biomass Bioenergy 2005;28:490–8.
[21] Stampfl PF, Clifton-Brown JC, Jones MB. European-wide GIS-based modelling system for quantifying the feedstock from Miscanthus and the potential contribution to renewable energy targets. Global Change Biol 2006.
[22] Lewandowski I, Clifton-Brown J, Andersson B, Basch G, Christian DG, Jørgensen U, et al. Environment and harvest time affects the combustion qualities of Miscanthus genotypes. Agronomy J 2003;95:1274–80.
[23] Clifton-Brown J. Personal communication; 2006.
[24] Elbersen HW, Bakker RR, Elbersen BS. A simple method to estimate practical field yields of biomass grasses in Europe. 14th European Biomass Conference: Biomass for Energy, Industry and Climate Protection. Paris, France; 2005.
[25] Scurlock J. Bioenergy feedstock characteristics. Oak Ridge, TN, U.S.A.: Oak Ridge National Laboratory, Bioenergy Feedstock Development Programs; 2005. p. 2.
[26] Van den Broek R, van den Burg T, van Wijk A, Turkenburg W. Electricity generation from eucalyptus and bagasse by sugar mills in Nicaragua: a comparison with fuel oil electricity generation on the basis of costs, macro-economic impacts and environmental emissions. Biomass Bioenergy 2000;19:311–35.
[27] AAEA. Commodity costs and returns estimation handbook. Ames, Iowa, U.S.A.: American Agricultural Economics Association; 2000. p. 566.
[28] Turnhollow A. Methodology for costing production and delivery options for energy crops. Oak Ridge, Tenessee, U.S.A.: Oak Ridge National Laboratory (ORNL); 2002. p. 13.
[29] Börjesson P. Environmental effects of energy crop cultivation in Sweden – Part I: Identification and quantification. Biomass Bioenergy 1999;16:137–54.
[30] EU. Eurostat database. Brussels, Belgium: Statistical Office of the European Communities; 2006. Accessible via http://epp.eurostat.cec.eu.int.
[31] IEA. World Energy Outlook 2007. Paris, France: International Energy Agency; 2007.
[32] EEA. The pan-European environment: glimpses into an uncertain future. Copenhagen, Denmark: European Environmental Agency (EEA); 2007. p. 42 plus Appendixes.
[33] De Wit MP, Faaij APC, Fischer G, Prieler S, Van Velthuizen HT. Biomass Resources Potential and Related Costs. The Cost-Supply Potential of Biomass Resources in the EU-27, Switzerland, Norway and the Ukraine. Utrecht, the Netherlands and Laxenburg, Austria: Copernicus Institute, Utrecht University, the Netherlands and the International Institute of Applied Systems Analysis (IIASA), Austria; 2008. p. 122.
[34] Bullard M, Metcalfe P. Estimating the energy requirements and CO_2 emissions from production of the perennial grasses miscanthus, switchgrass and reed canary grass. ADAS Consulting Ltd. on behalf of Department of Trade and Industry; 2001.
[35] FAIR. Switchgrass (Panicum vigatum L.) as an alternative energy crop in Europe; 2001. p. 85 plus Appendixes.
[36] Christian DG, Riche AB. Establishing fuel specifications of non-wood biomass crops. Harpenden, United Kingdom: IACR-Rothamsted and EPR Ltd; 1999. p. 64 plus Appendixes.
[37] Lewandowski I. Personal communication; 2006.
[38] Bullard MJ, Nixon P. Miscanthus agronomy. London/Ely, U.K.: Ministry of Agriculture, Fisheries and Food/ADAS Arthus Rickwood; 1999. p. 61.
[39] Biewinga EE, Van der Bijl G. Sustainability of energy crops in Europe. Utrecht, the Netherlands: Centre for Agriculture and the Environment (CLM); 1996. p. 124 plus Appendixes.
[40] Lemus R, Brummer EC, Moore KJ, Molstad NE, Burras CE, Barker MF. Biomass yield and quality of 20 switchgrass populations in southern Iowa, USA. Biomass and Bioenergy 2002;23:433–42.
[41] Lewandowski I, Clifton-Brown JC, Scurlock JMO, Huisman W. Miscanthus: European experience with a novel energy crop. Biomass and Bioenergy 2000;19:209–27.
[42] Lewandowski I, Kicherer A, Vonier P. CO_2-balance for the cultivation and combustion of Miscanthus. Biomass and Bioenergy 1995;8:81–90.
[43] Christian DG, Bullard MJ, Wilkins C. The agronomy of some herbaceous crops grown for energy in Southern England. Aspects Appl Biol 1997;49:41–51.
[44] Sanderson MA, Egg RP, Wiselogel AE. Biomass loss during harvest and storage of switchgrass. Biomass Bioenergy 1997;12:107–14.
[45] Hartmann D, Schön H. Analyse und Bewertung der Systeme zur Hochdruckverdichting von Halmgut. München, Germany: Institut und Bayerische Landesanstalt für Landtechnik der Technischen Universität München-Weihenstephan; 2004. p. 63 plus Appendixes.
[46] Thek G, Obernberger I. Wood pellet production costs under Austrian and in comparison to Swedish framework conditions. Biomass Bioenergy 2004;27: 671–93.
[47] Delaruea E, Lambertsa H, D'haeseleer W. Simulating greenhouse gas (GHG) allowance cost and GHG emission reduction in Western Europe. Energy 2007;32:1299–309.
[48] Perlack RD, Turhollow AF. Assessment of options for the collection, handling, and transport of corn stover. Oak Ridge, Tennessee, U.S.A.: Oak Ridge National Laboratory; 2002. p. 29.
[49] Brusse A. Personal communication. Rotterdam, the Netherlands: European Bulk Services; 2006.
[50] LPDAAC. Global Land Cover Characterisation database – IGBP classification. Version 2.0 ed: Located at the U.S. Geological Survey's EROS Data Center, Accessible via: www.LPDAAC.usgs.gov, Land Processes Distributed Active Archive Center; 2003.
[51] Wischmeier WH, Smith DD. Predicting rainfall-erosion losses from cropland east of the Rocky Mountains: Guide for selection of practices for soil and water conservation: United States Department of Agriculture. Handbook no. 282; 1965.
[52] Wischmeier WH, Smith DD. Predicting rainfall-erosion losses: a guide to conservation planning. Handbook no. 537. United States Department of Agriculture; 1978.
[53] Renard KG, Freimund JR. Using monthly precipitation data to estimate the R-factor in the revised USLE. J Hydrol 1994;157:287–306.
[54] IIASA, FAO. Global Agro-ecological Assessment for Agriculture in the 21st century: Methodology and Results. Laxenburg, Austria; Rome, Italy: International Institute of Applied Systems Analysis (IIASA), United Nations Food Agricultural Organisation (FAO); 2002. p. 119.
[55] USDA. National soil survey handbook. U.S. Department of Agriculture, Natural Resources Conservation Service; 2005. Available: http://soils.usda.gov/technical/handbook/.
[56] Hall RL. Grasses for energy production – hydrological guidelines. London, United Kingdom: Department of Trade and Industry (DTI), Centre for Ecology and Hydrology; 2003. p. 15.
[57] Jankauskas B, Jankauskiene G. Erosion-preventive crop rotations for landscape ecological stability in upland regions of Lithuania. Agricult Ecosyst Environ 2003;95:129–42.
[58] Bical Energy. Miscanthus environmental profile. Bical Industrial Crops Ltd.; 2005. p. 10.
[59] Parrish DJ, Fike JH. The biology and agronomy of switchgrass for biofuels. Crit Rev Plant Sci 2005;24:423–59.
[60] McLaughlin SB, Walsh ME. Evaluating environmental consequences of producing herbaceous crops for bioenergy. Biomass Bioenergy 1998;14:317–24.
[61] DEFRA. Controlling soil erosion – Incorporating former advisory leaflets on grazing livestock, wind, outdoor pigs and the uplands. London, United Kingdom: Department for Environment, Food and Rural Affairs; 2005. p. 43.
[62] Jorgensen U, Schelde K. Energy crop water and nutrient use efficiency. Prepared for the International Energy Agency Bioenergy Task 17 Short Rotation Crops. Tjele, Denmark: Danish Institute of Agricultural Sciences; 2001.
[63] Stephens W, Hess T, Knox J. Review of the effects of energy crops on hydrology. Silsoe, United Kingdom: Institute of Water and Environment, Cranfield University; 2001. p. 58.
[64] Hall RL. Short Rotation Coppice for Energy Production – Hydrological Guidelines. London, United Kingdom: Department of Trade and Industry (DTI), Centre for Ecology and Hydrology; 2003. p. 21.
[65] Byrd GT, May PA. Physiological comparisons of switchgrass cultivars differing in transpiration efficiency. Crop Sci 2000;40:1271–7.
[66] Lewandowski I, Scurlock JMO, Lindvall E, Christou M. The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass Bioenergy 2003;25:335–61.
[67] LUC. Bioenergy: Environmental impact and best practice. Bristol, United Kingdom: Land Use Consultants; 2007. p. 150.

[68] Eppel-Hotz A, Jodl S. Comparative faunistic examination in Miscanthus (Miscanthus × giganteus), corn (Zea mays) and reed (Phragmites australis) expanses. Unpublished data; 1997.
[69] Jodl S, Eppel-Hotz A, Marzini K. Examination of the ecological value of miscanthus expanses – faunistic studies. Biomass for Energy and Industry, the 10th European Biomass Conference. Würzburg, Germany: C.A.R.M.E.N. Publishers; 1998. p. 778–9.
[70] Clifton-Brown J, Stampfl PF, Jones MB. Miscanthus biomass production for energy in Europe and its potential contribution to decreasing fossil fuel carbon emissions. Global Change Biol 2004;10:509–18.
[71] IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4 Agriculture, Forestry and Other Land Use. IPCC, IGIS; 2006.
[72] Smeets EMW, Bouwman AF, Stehfest E, Van Vuuren DP, Postuma A. The contribution of N_2O emissions to the greenhouse gas balance of first-generation biofuels (accepted for publication). Global Biochem Cycles 2008.
[73] Delucchi MA, Lipman T. A Lifecycle Emissions Model (LEM): Lifecycle Emissions From Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials. Appendix C: Emissions related to cultivation and fertilizer use. Davis, CA, USA: Institute of Transportation Studies, University of California; 2003. p. 84.
[74] FAO. FAOSTAT database collections. Rome, Italy: Accessible via: http://apps.fao.org/page/collections. Food and Agriculture Organisation of the United Nations; 2007.
[75] Kumar A, Sokhansanj S. Switchgrass (Panicum vigratum L.) delivery to a biorefinery using integrated biomass supply analysis and logistics (IBSAL) model. Biores Technol 2007;98:1033–44.
[76] Hamelinck CN, Suurs RAA, Faaij APC. International bioenergy transport costs and energy balance. Biomass Bioenergy 2005;29:114–34.
[77] NEA. Factorkosten van het goederenvervoer: een analyse van de ontwikkeling in the tijd (in Dutch). Rijswijk, the Netherlands: Adviesdienst Verkeer en Vervoer/NEA Transportonderzoek en -opleiding; 2004. p. 60 plus Appendices.
[78] Van Dam J, Faaij APC, Lewandowski I, Fischer G. Biomass production in Central and Eastern Europe under different scenarios. Biomass Bioenergy 2007;31: 345–66.
[79] Ney RA, Schnoor JL. Incremental life cycle analysis: using uncertainty analysis to frame greenhouse gas balances from bioenergy systems for emission trading. Biomass Bioenergy 2002;22:257–69.
[80] Smeets EMW, Faaij APC. The Economic Performance and Greenhouse Gas Balance of 15 different Miscanthus and Switchgrass Applications in Europe, in preparation.
[81] EEA. How much bioenergy can Europe produce without harming the environment? Copenhagen, Denmark: European Environment Agency (EEA); 2006. p. 59 plus Appendixes.
[82] Edwards W. Machinery management. Farm machinery selection. Ames, Iowa, USA: Iowa State University, Extension Service; 2001. p. 8.
[83] Carver P. Personal communication with P. Carver of Bical; 2006.
[84] Easterby-Trailers. Easterby-Trailers price list. Cottam Grange, United Kingdom: Easterby Trailers; 2006. Accessible via: www.easterbytrailers.co.uk/.
[85] Kamps-de-Wild. Kamps de Wild agricultural machinery – price list. Zevenaar, the Netherlands; 2006.
[86] Kverneland. Kverneland price list. Kvernaland, Norway; 2006. Accessible via: www.kverneland.com.
[87] Lazarus W, Selley R. Farm machinery economic cost estimates for 2004. St. Paul, Minnesota, U.S.A.: University of Minnesota, Extension Service; 2003. p. 11.
[88] Tractor-Outlet. Tractor-Oulet price list. Christmas Valley, Oregon, U.S.A.; 2006. Available on the internet via: www.tractor-outlet.com.
[89] Lewandowski I, Clifton-Brown J, Andersson B, Basch G, Christian DG, Jorgensen U, et al. Environmental and harvest time affects the combustion qualities of Miscanthus genotypes. Agronomy J 2003;95:1274–80.
[90] Kaltschmitt M, Reinhardt GA. Nachwachsende Energieträger. Grundlagen, Verfahren, ökologische Bilanzierung. Braunschweig/Weisbaden: Verlag Verwieg; 1997.
[91] Wood S, Cowie A. A Review of Greenhouse Gas Emission Factors for Fertiliser Production. Research and Development Division, State Forests of New South Wales; Cooperative Research Centre for Greenhouse Accounting for the International Energy Agency Bioenergy Task 38; 2004. p. 20.
[92] Ramaswamy V, Forster P, Artaxo P, Berntsen, T, Betts, R, Fahey, DW, et al. Changes in Atmospheric Constituents and in Radiative Forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, et al., editors. Climate Change 2007: The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom, New York, USA: Cambridge University Press; 2007.
[93] Bos AJM. Direction indirect: the indirect energy requirements and emissions from freight transport; 1998.
[94] Stone R, Hilborn D. USLE fact sheet. Ministry of Agriculture of Ontario; 2000.
[95] Ma J. Combining the USLE and GIS/ArcView for Soil Erosion Estimation in the Fall Creek Watershed in Ithaca (New York). Ithaca, New York, USA: Cornell University; 2001.
[96] Gray DH, Sotir RB. Biotechnical and soil bioengineering slope stabilization: a practical New York. NY, USA: Wiley-Interscience; 1996.